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Updates on the AZGS Geologic Mapping Program

by Carson A. Richardson and Philip A. Pearthree

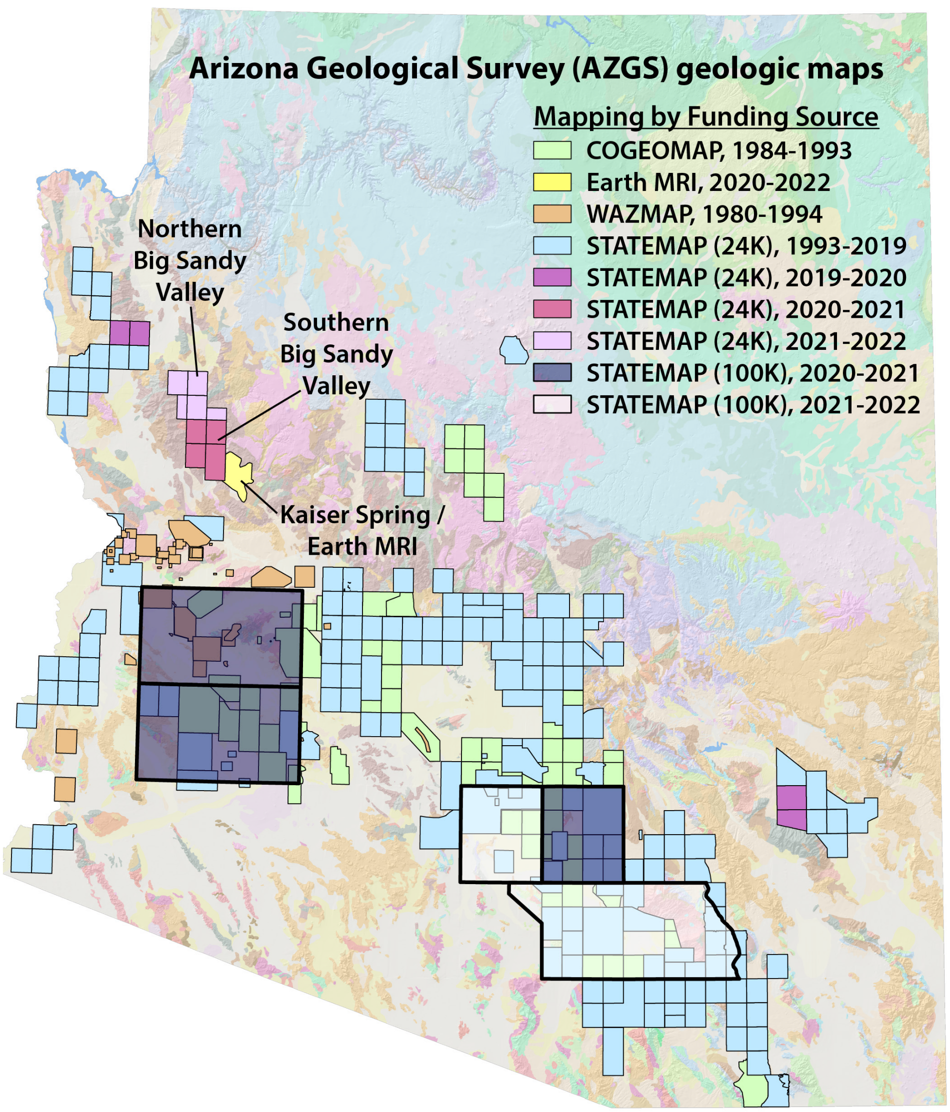

***Figure 1**. Geologic map of Arizona, showing areas that have been mapped since 1979 by the Arizona Geological Survey, and keyed by funding sources.*

Arizona is a geologically diverse, mineral-rich state that has seen steady population growth over the last four decades as people relocate to Arizona for our stunning landscapes, pleasant winter climate, and burgeoning economy. A growing population requires additional natural resources and land for development that, alongside exacerbated drought conditions and enhanced geologic hazards such as wildfires and earth fissures, can lead to land use conflicts. Questions that quickly arise during periods of growth include: Where are aggregate resources needed for development? What is the potential for basins to host groundwater resources? Where will we find the metallic mineral resources necessary for economic development in the 21st century? What natural hazards might present a danger to existing development and developing areas? What is the best use of the land?

One of the most significant contributions a state geological survey can make is to conduct basic geologic mapping to empower stakeholders with the necessary information to address these difficult questions. Geologic mapping depicts the dis-

ALSO IN THIS ISSUE

Mission

To inform and advise the public about the geologic character of Arizona in order to increase the understanding and encourage prudent development of the State's land, water, mineral, and energy resources.

Activities

Public Information

Inform the public by answering inquirings, maintaining a library, databases, online repositories, and a website, giving talks, and leading fieldtrips.

Geologic Mapping

Map and describe the origin and character of rock units and their weathering products.

Geologic Hazards

Investigate geologic hazards and limitations such as earthquakes, land subsidence, flooding, and rock solution that may affect the health and welfare of the public or impact land and resource management.

Energy and Mineral Resources

Describe the origin, distribution, and character of metallic, nonmetallic, and energy resources and identify areas that have potential for future discoveries.

Cover photo: Bald eagle soaring over the Sonoran Desert near Lake Pleasant, central Arizona. Photo © Ted Grussing

tribution, composition, and structure of geologic materials at the surface and at depth. Geologic maps are used by governmental planning entities to document the location of resources prior to development, by private industry to stimulate exploration for natural resources, and by developers for ensuring their communities account for and mitigate risks from natural hazards (among other applications!). Fortunately, the importance of geologic mapping to society has been recognized at both federal and state levels, and the funding available for geologic mapping has increased substantially in the past several years.

An Abbreviated History of Geologic Mapping in Arizona since 1979

The Arizona Geological Survey (in its various forms) has been conducting geologic mapping almost since its inception in 1915. The pace of geologic mapping increased dramatically after a formal geologic mapping program was organized in 1979 (Fellows and Spencer, 2004). In the 1980's, AZGS mapping was initially focused on 1:24,000 scale mapping of western Arizona (informally referred to as the Western Arizona Mapping Project, or WAZMAP), as the area had complex and poorly understood geology, and hosted detachment-related iron oxide-copper-gold (IOCG) mineralization that were also not well understood at the time. In 1984, the United States Geological Survey (USGS) established the Cooperative Geological Mapping (COGEOMAP) Program as a cost-sharing effort to encourage states to undertake new geologic mapping. The increase in available funds for mapping allowed the geological survey to hire additional seasonal mappers and systematically map the bedrock geology of the Phoenix 1° x 2° quadrangle (Reinhard and Miller, 1987; Reynolds et al., 2013). Surficial geologic mapping began in earnest in the late 1980s. The COGEOMAP program was in place from 1984-1993; AZGS was awarded $495,922 in federal funds and provided slightly more in state matching funds from AZGS's line-item appropriation from the legislature.

The National Geologic Mapping Act of 1992 established the National Cooperative Geologic Mapping Program (NCGMP) with FEDMAP, STATEMAP, and EDMAP components. EDMAP offers cooperative funding agreements to universities for students to conduct geologic mapping projects to foster the next generation of geologic mappers. FEDMAP directs the USGS to develop geologic maps and complementary data to increase our understanding of the national geologic framework. STATEMAP provides cooperative agreements to state geological surveys to conduct new geologic mapping on societally relevant issues, with 1:1 matching state and federal funding. Additionally, the STATEMAP program specified that the states establish advisory panels, representing the broad users of geologic maps, who shall determine the mapping priorities of each state in consultation with the State Geologist.

For the first decade of the STATEMAP program, Arizona's advisory panel recommended mapping to be focused on the Phoenix-Tucson corridor, an area that while only representing 20% of Arizona's land is home to 80% of its residents. By 2004, much of the Phoenix-Tucson corridor was mapped, and the loci of mapping has since migrated across the state, including southeastern Arizona (Safford and the San Pedro River Valley), the Lower Colorado River Corridor, as well as returning to western Arizona. Between 1993-2020, AZGS was awarded $4.59 million in federal funds and provided $4.61 million in state matching funds to conduct geologic mapping through the STATEMAP program.

Recent Changes to STATEMAP and New Mapping Opportunities

For Federal Fiscal Year 2021 (starting October 2020), Congress increased the available funding for the NCGMP to encourage contributions towards a new national geologic map through the development of intermediate-scale geologic maps (typically 1:100,000-scale) that utilize a standardized geodatabase format for easy integration (now referred to as the US GeoFramework Initiative). In response to this opportunity, AZGS mapping efforts have evolved to contribute to the national effort while continuing to meet the geologic mapping needs of Arizona's citizenry. AZGS geologists continue to do detailed 1:24,000 geologic mapping, with a current focus on the I-11 corridor in Big Sandy Valley in Mohave County (see below). Contemporaneously, AZGS geologists are undertaking digital compilations of 1:100,000 geologic mapping in west-central Arizona and southern Arizona.

Additionally, the USGS created the Earth Mapping Resources Initiative (Earth MRI) in 2019 to identify and map areas with the potential to contain undiscovered critical mineral resources. These are resources identified by the USGS that are critical to the economic and national security of the United States, many of which are mined and manufactured primarily or entirely outside of the country. AZGS was selected to undertake a two-year project exploring the distribution and origins of sedimentary lithium mineralization in the greater Big Sandy Valley area.

With the recent increases in available funding, AZGS has undertaking some of the largest geologic mapping projects in the history of the state. Between the most recent two STATEMAP projects and the Earth MRI project, AZGS will expend over $1.5 million dollars (Table 1) on geologic mapping from September 2020 to September 2022. This represents a significant investment in basic geologic research that will be freely available to anyone interested in Arizona geology.

Table 1. Recent Funding Amounts for Geologic Mapping in Arizona

Project	Federal Funding	State Match	Project Total
STATEMAP 2020-2021	$324,016	$324,016	$638,032
Earth MRI 2020-2022	$100,000	$50,322	$150,322
STATEMAP 2021-2022	$379,908	$379,913	$759,821
Total Mapping Funds 2020-2022	***$803,924***	***$754,251***	***$1,558,175***

Geologic Mapping in the Big Sandy Valley and Environs

AZGS began a focused mapping campaign in the Big Sandy Valley area in Fall 2020 (Fig. 1). This mapping campaign encompasses two complementary mapping projects funded by the STATEMAP and Earth MRI programs. The STATEMAP project in the current cycle focused on four and a half 7.5′ quadrangles in the southern Big Sandy Valley and the adjacent bedrock mountains; it includes the Big Sandy lithium deposit, hosted in lacustrine deposits. The 2-year Earth MRI project focuses on the Kaiser Spring volcanic field and adjacent basin deposits, located between Wikieup and Bagdad, and includes the Burro Creek lithium deposit.

The Big Sandy Valley was proposed and selected by the AZGS advisory panel due to several societal and scientific topics that could be addressed through new geologic mapping, including: aggregate resources, potential hazards related to the future Interstate 11, and interrelation of the Big Sandy basin and mineral resources. The future Interstate 11, running from Nogales, Arizona to near Reno, Nevada, will follow the route of US-93 through Big Sandy Valley, requiring the location of future aggregate resources needed for construction and the identification of potential flood hazards and varying geologic substrates along the route. In the past few years, two sedimentary lithium deposits (the Big Sandy lithium deposit held by Hawkstone Mining and the Burro Creek lithium deposit held by Bradda Head) in the greater Big Sandy Valley area have been discovered and now have defined mineral resources.

Lithium has been demonstrated elsewhere to be leached from silicic volcanic rocks and redeposited in clay developed in ash-rich sediments in adjacent, typically closed, basins (Vine, 1980; Benson et al., 2017). Thus, one of the principal aims of the STATEMAP project is to constrain the timing of basin development, closure, and integration of the Big Sandy Valley into the larger Bill Williams River watershed. The complementary Earth MRI project addresses the volcanic rocks as a potential source of lithium, as well as representing a potential dam-inducing event that may have closed the Big Sandy basin. Additionally, the Big Sandy Valley area has been the site of past and current exploration efforts for porphyry copper, uranium, epithermal gold-silver, and pegmatite-related rare earth element mineralization.

Starting in September 2021, AZGS will begin mapping the northern half of Big Sandy Valley. This will allow AZGS to define the spatial extent and character of the ancestral Big Sandy Basin, document the structures and faults involved with basin development, and better describe the diverse mineral resources in the field area.

Compilation Geologic Mapping

The other major component to the current STATEMAP program is compilation of intermediate-scale geologic maps using a common geodatabase standard called GeMS. These efforts particularly address the objectives of the US GeoFramework Initiative, which aims to create a variable-scale, national integrated 2D and 3D geologic map database that provides for the seamless construction of maps across state boundaries that resolves nomenclature differences.

This past year, AZGS has been revising and updating previous 1:100,000-scale compilations of the Salome and Little Horn Mountains 30′ x 60′ sheets, as well as the eastern half of the Casa Grande 30′ x 60′ sheet. This coming year, AZGS will be producing two new 1:100,000 compilation geologic maps. One map will be the western half of the Casa Grande 30′ x 60′ sheet. The other compilation map will span the greater Tucson area from the San Pedro River in the east to the Waterman, Roskruge, and Silver Bell Mountains in the west (Fig. 1). As compilation mapping scales up from more detailed mapping, future 100K compilation maps will likely align with areas where AZGS has conducted detailed 24K mapping.

To assist our compilation mapping efforts, in the next year we will be developing a toolbar for the new ArcGIS platform (ArcGIS Pro) to develop an efficient workflow with the USGS GeMS geodatabase standard. When completed, this toolbar will be freely available to other state geological surveys and members of the public interested in contributing to the US GeoFramework Initiative.

Conclusion

In summary, this coming year AZGS will receive $379K in federal funding and will match that with state funding, for a grand total of $759K. We will use this funding to conduct new detailed geologic mapping in northwestern Arizona and intermediate-scale compilation mapping of southern and central Arizona. New geologic mapping is only possible through the state appropriation allocated to the AZGS as a line-item in the University of Arizona budget, as all federal STATEMAP funding must be matched with state funds dollar-for-dollar. AZGS remains extremely grateful for the continued support from the State Legislature, the Governor's Office, and our many stakeholders.

References

Benson, T. R., Coble, M. A., Rytuba, J. J., and Mahood, G. A., 2017, Lithium enrichment in intracontinental rhyolite magmas leads to Li deposits in caldera basins: Nature Communications, v. 8, p. 270.

Fellows, L. D., and Spencer, J. E., 2004, Geological Mapping in Arizona: Arizona Geology, v. 34, no. 4, p. 1-2.

Reinhardt, J., and Miller, D. M., 1987, COGEOMAP: A new era in cooperative geologic mapping: U.S. Geological Survey Circular 1003, 12 p.

Reynolds, S. J., Spencer, J. E., Richard, S. M., and Pearthree, P. A., 2013, The Geological Exploration of Arizona: The Role of State and Federal Surveys and the Geological Map of Arizona: Arizona Geology Magazine.

Vine, J. D., 1980, Where on Earth is all the lithium?: U.S. Geological Survey Open-File Report 80-1234, 107 p.

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https://azgs.arizona.edu/about/staff

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AZGS Document Repository
http://repository.azgs.az.gov/

AZGS Mining Data
minedata.azgs.arizona.edu

New Publications

Ben-Horin, J.Y., Pearthree, P.A., Gootee, B.F., and Rittenour, T., 2021, [Recency and size of young displacements along the Mead Slope fault, Lake Mead Area, Arizona](): Arizona Geological Survey Open-File Report 21-01, 14 p.

The Mead Slope fault (MSF) has been considered an active late Quaternary fault for several decades; however, constraints on slip rates and on the age and size of surface-rupturing earthquakes were underdeveloped. We used high-resolution DEMs generated from multiple drone flight and ground-control points and aerial imagery to map the fault in detail. We determined that the fault consists of two main strands, both offsetting Quaternary alluvial fan remnants. The northwestern strand offsets late to latest Pleistocene fan deposits, as well as relatively young tributary gravel deposits exposed below a wave-cut bench associated with past high levels of Lake Mead. Examination of this exposure revealed 3 identifiable surface ruptures. Based on Optically-Stimulated Luminescence dating (OSL), the latest two events occurred within the last ~25,000 years to 60,000 years. In addition, we collected 18 3He cosmogenic surface rock samples to date various Quaternary landforms displaced by the fault. Sampling efforts for the cosmogenic dates concentrated on early to middle Pleistocene landforms due to the high age inheritance of the younger fan surfaces. We tentatively estimate the slip rate to range from 0.06mm/yr to 0.13mm/yr based on amount of offset of Qi3-4 channels and the correlation of the soil ages from the wave cut exposure.

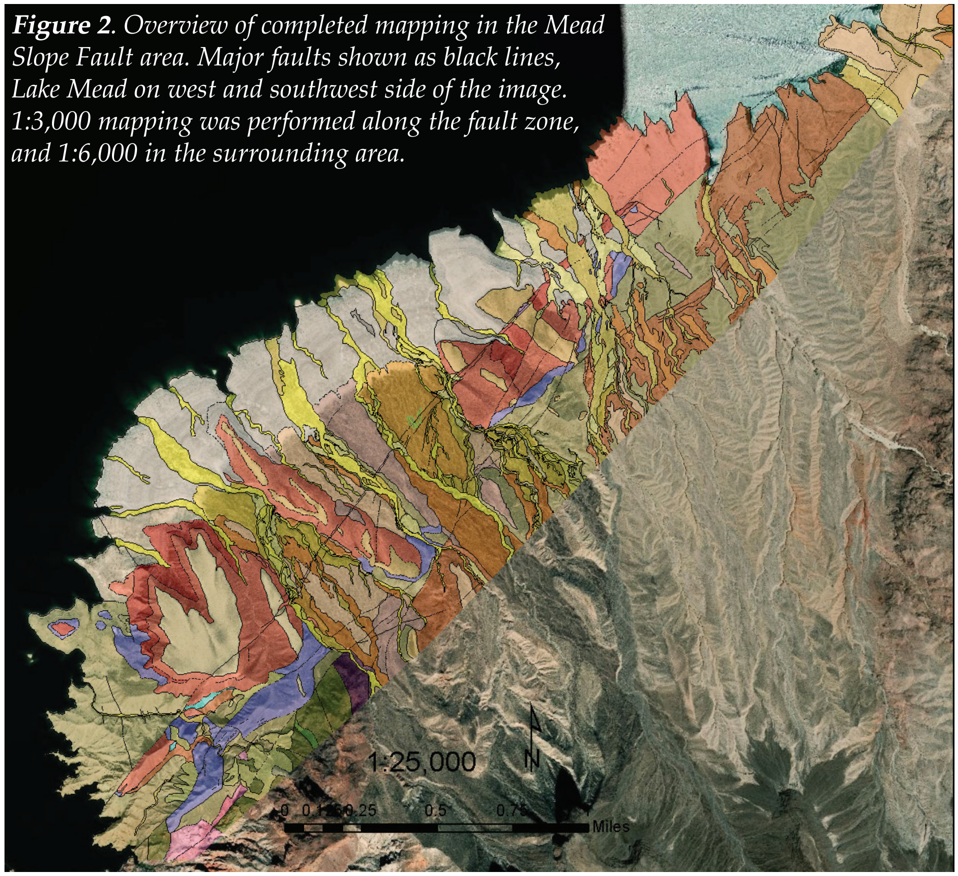

***Figure 2**. Overview of completed mapping in the Mead Slope Fault area. Major faults shown as black lines, Lake Mead on west and southwest side of the image. 1:3,000 mapping was performed along the fault zone, and 1:6,000 in the surrounding area.*

Ben-Horin, J.Y., Pearthree, P.A., Holm, R.F., and Heizler, M., 2021, [Detailed geologic and geomorphic mapping and characterization of the Lake Mary Fault Zone](): Arizona Geological Survey Open-File Report 21-02, 16 p.

The Lake Mary Fault System (LMFS) is located near Flagstaff, Arizona. Prior to this study, little was known of its slip rate and whether the fault system was active. The LMFS is a 30-45 km long set of normal faults with multiple splays that displace Pliocene-Quaternary lava flows and sediments. Detailed mapping identified offset lava flows, two of which are Quaternary in age, and resulted in the discovery of less active fault strands in the southern portion of the mapping

***Figure 3**. Lake Mary Fault trace exposed along U.S. Forest Service Road 128 just below the Lowell Observatory Perkins Telescope. Photo mosaic by B. Gootee.*

area. In addition, detailed mapping provided the geologic constraints for locating potential paleoseismic sites. The LMFS has segments that have been active for several million years with a complex history resulting in dense fracturing of bedrock and reactivation of older reverse and normal faults. The Lake Mary fault, the active strand of the LMFS, appears to be a normal fault with a steep dip and strike that varies from N60° W to N-S. The main trace of the Lake Mary fault has up to 40 m of vertical offset of a colluvial deposit with clasts from a Quaternary basaltic lava flow, dated for this study with ^{40}Ar/^{39}Ar at 1.17 ± 0.0017 Ma. Geochemical analyses of volcanic clasts found in the Lake Mary fault footwall corroborated the hand identification showing the clasts' originating from the Qbwc flow. Slip rate estimates were calculated using 40Ar/39Ar dates obtained for this study and the vertical offset measurements of Tob (5.9Ma) and Qbwc (<1.17Ma) for a slip rate range of 0.022 mm/yr to 0.035 mm/yr.

Holm, R.F., 2021, Petrography, geochemistry, and volcanogenic development of the San Francisco Mountain volcanic system, northern Arizona: Arizona Geological Survey Contributed Report 21-C, 36 p., 5 appendices.

San Francisco Mountain and eight satellite slicic volcanoes at its base constitute the San Francisco Mountain volcanic system. The central composite volcano is the largest edifice in the San Francisco volcanic field, a basaltic field on the southwestern margin of the Colorado Plateau in northern Arizona. Satellite volcanoes range from single domes to clusters of as many as eight domes. Vent locations and many internal volcano structures (dikes) coincide with pre-volcanic crustal structures on northwest, north, and northeast trends. The volcanic system was active from late Pliocene to late Pleistocene (2.78-0.091 Ma). Lava erupted in four stages, or compositional cycles, each beginning with rhyolite or dacite domes. The first three stages ended with andesite stratovolcanoes, but the fourth stage erupted only minor andesite.

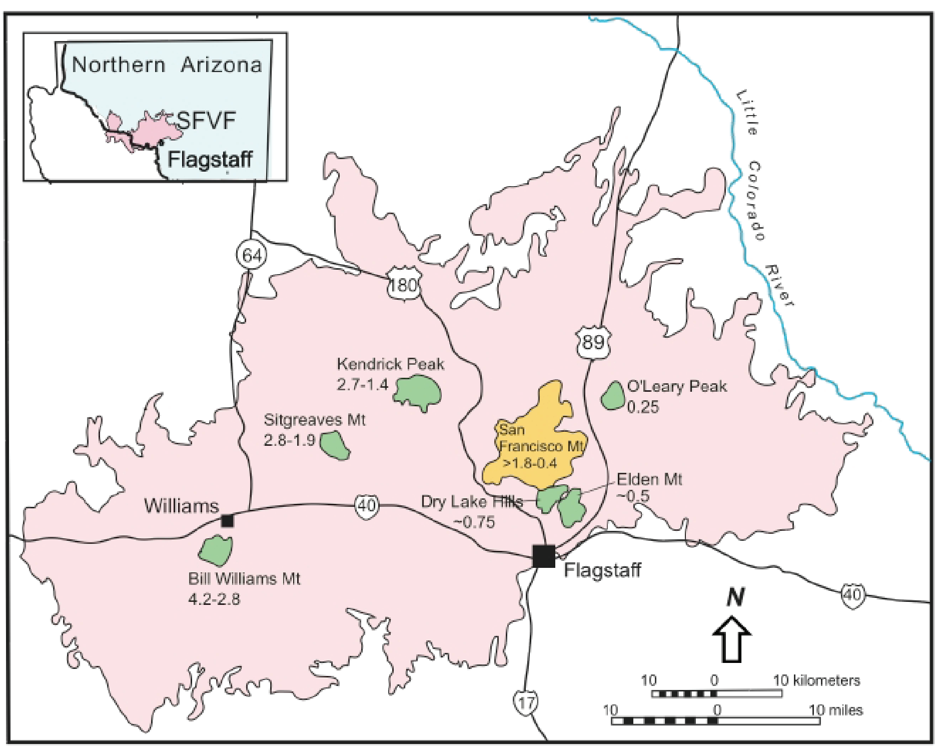

***Figure 4**. Map of the San Francisco volcanic field, with San Franscisco Mountain in gold.*

New External Grants

In addition to the U.S. Geological Survey's STATEMAP program, AZGS has successfully obtained funding from other state and federal agencies. The following details several of our recent successful grants.

Holocene mapping of riparian and intermittent streams within the Verde River watershed
Arizona Department of Water Resources, $214,000
Duration: 4/30/2021 to 4/30/2022
AZGS Principal Investigator (PI): Joe P. Cook

The key objectives are to conduct Holocene mapping along a number of currently or historically riparian and intermittent streams within the Verde River watershed to delineate the extent of recent river alluvium along each stream. The ADWR will leverages these data to differentiate between surface and groundwater use as defined by the Arizona courts. The funding level is fluid and determined by how many streams we map. At a maximum, the study could include 25 streams.

Seismic loadings and ground motion time histories for Horse Mesa Dam and Mormon Flat Dam
U.S. Bureau of Reclamation, $98,272
Duration: 5/01/2021 to 4/30/2023
AZGS Principal Investigator (PI): Jeri Y. Ben-Horin

The primary goal of the Reclamation's project in central Arizona is to update the seismic loadings and the ground motion time histories for Horse Mesa Dam and Mormon Flat Dam on the Salt River. The most recent seismic loadings for Horse Mesa Dam and Mormon Flat Dam were computed 20 years ago and are outdated (Wong, 2000). In order to update the seismic loadings, the fault sources and background seismicity sources need to be revised.

Three faults within about 50 km of Horse Mesa and Mormon Flat dams have been identified as active: the Sugarloaf fault about 15 km from the dams, the Carefree fault about 43 km from Horse Mesa Dam and about 38 km from Mormon Flat Dam, and the Horseshoe fault about 50 km from the two dams (Figure 1). Because of their proximity to the dams, the Sugarloaf fault and the Carefree fault will be the focus of the geologic studies to revise the fault sources. Geomorphic mapping and field reconnaissance will be part of a first phase of study to evaluate the Sugarloaf and Carefree faults. A second phase that includes detailed geologic field data collection for these two faults may be recommended depending on the results of the first phase of study. In addition, lineaments that could be indicative of Quaternary fault activity on previously identified older faults or previously unidentified faults may be examined.

The primary goal of the fault studies is to determine the likelihood that the fault is active, the type of rupture expected, the potential rupture length, and the fault activity rate based on the either the recurrence interval between surface ruptures or fault slip rate. Possible ranges of values for these parameters based on geologic field data, if possible, are needed for input into the probabilistic seismic hazard analysis for Horse Mesa Dam and Mormon Flat Dam.

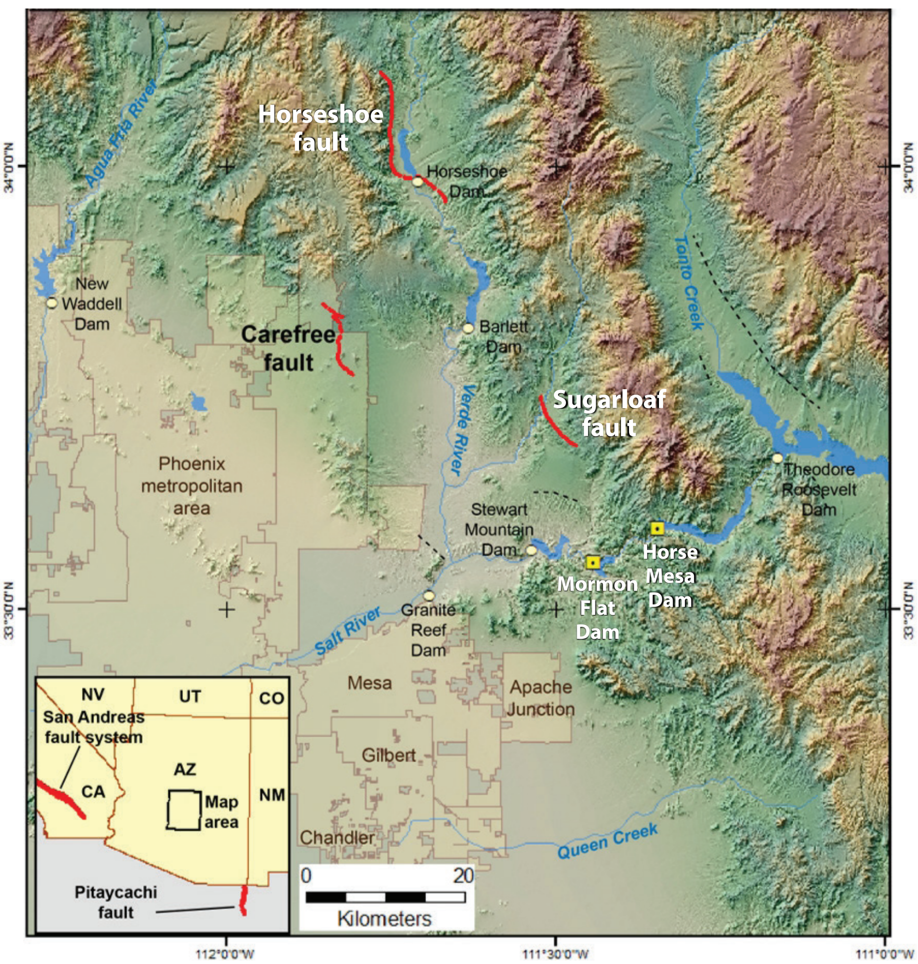

***Figure 5**. Map showing faults and dams in central Arizona, with Horse Mesa Dam and Mormon Flat Dam shown with yellow squares. Red lines are late Quaternary fault traces from the U.S. Geological Survey (http://earthquake.usgs.gov/regional/qfaults).*

References

Wong, I., 2000, Probabilistic seismic hazard analysis of Horse Mesa and Mormon Flat Dams, southern Arizona: URS Greiner Woodward Clyde, Federal Services; Memorandum from I. Wong to Jon Ake, Bureau of Reclamation and transmitted to Dave Hinchliff, Senior Dam Engineer. Bureau of Reclamation, Denver, Colorado, February 3, 2000.

2021-2022 Data Preservation and Critical Minerals Activities in Arizona

National Geological and Geophysical Data Preservation Program, U.S. Geological Survey, $83,978
Duration: 8/31/2021 to 8/29/2022
AZGS Principal Investigators (PI): Andrew A. Zaffos and Carson A. Richardson

The key objectives of the upcoming AZGS data preservation proejct are to: 1) increase availabity of our data and materials by digitally preserving geologic map data created prior to the adoption of GIS, and 2) compile mineral deposit data for Pinal County to develop a centrally-located, modern review publication on the mineral resources for use by the public. Pinal County hosts ~30% of Arizona's known porphyry copper deposits, in addition to a diversity of other mineral resources, and lies along the Arizona Sun Corridor, host to much of Arizona's population.

The final deliverables from this project will include GeMS-compliant geodatabases for 25 AZGS paper maps that currently only exist as PDF's and an AZGS review publication on the "*Mineral Resources of Pinal County, Arizona.*"

Mitigating Earthquake Hazards in Arizona: An Update

The AZGS works closely with the mitigation team at Arizona's Department of Emergency and Military Affairs and with the Arizona Council on Earthquake Safety (Ramon Arrowsmith ASU Chair; Jeri Y. Ben-Horin AZGS Vice-Chair) to inform decision-makers, those in the education and health communities, and the public to the scope of Arizona's earthquake hazards and best practices for mitigating those hazards.

National Earthquake Hazard Reduction Program funding this fiscal year was leveraged to provide virtual National Earthquake Technical Assistance Program (NETAP) training for managing the impact of natural hazards. We partnered with John Crofts (Utah Earthquake Program Manager) and Janell Woodward (Nevada State Hazard Mitigation Officer) to provide FEMA NETAP training for Arizona, Nevada and Utah schools and hospitals via the following courses.

FEMA P-1000 (April 22, 2021) Safer, Stronger, Smarter: A Guide to Improving School Natural Hazard Safety. Training by Ines Pearce. Virtual audience included 22 Arizonans: school administrators, facilities managers, and teachers and staff at K-12 schools. Training included authoritative information and guidance and guidance to develop a comprehensive strategy for addressing natural hazards at schools. The guidance included information about the physical protection of school facilities and school operations before, during, and after an event.

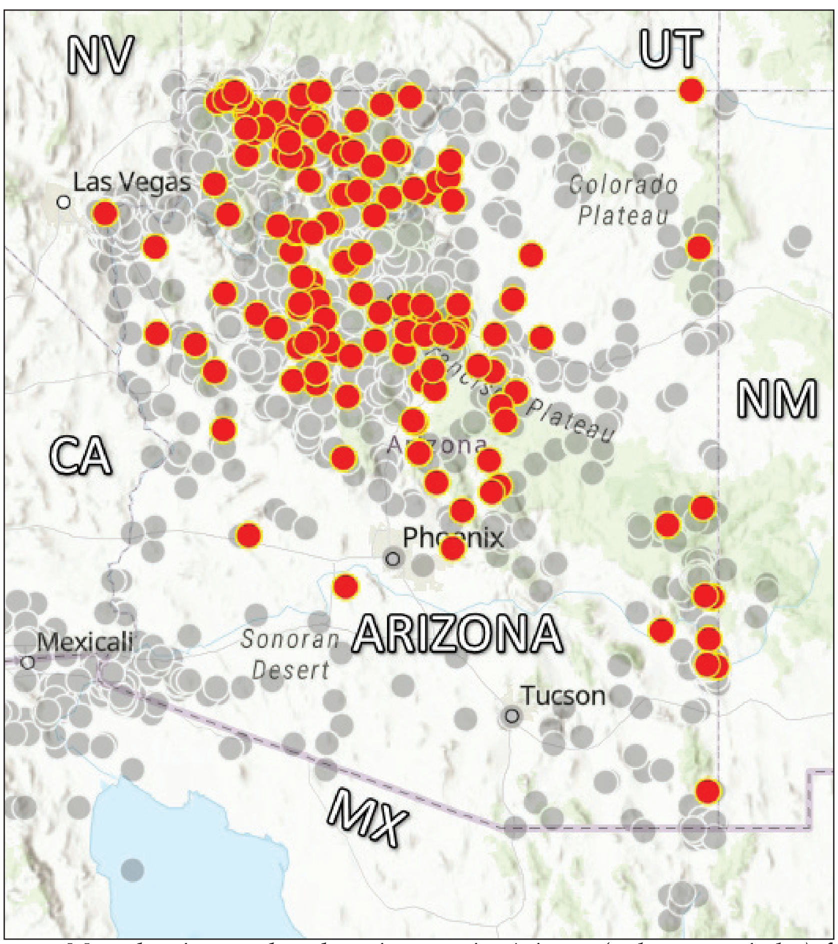

Figure 6*. Map showing earthquake epicenters in Arizona (red-orange circles) for the 12-month period from June 10, 2020 to June 20, 2021. Gray circles represent historic earthquake epicenters recorded prior to June 9, 2020. Figure is courtesy of Jeri Y. Ben-Horin, Manager of the Arizona Broadband Seismic Network.*

FEMA P-767 (May 20, 2021) Earthquake Mitigation for Hospitals; training by Barry Welliver. The virtual audience included 24 Arizonans representing medical facilities from across the state. Training focused on earthquake hazards in health care settings and methods to analyze and reduce risks of damage in hospitals and other medical buildings.

FEMA 395 (May 25, 2021) Earthquake Safety and Mitigation for Schools; training by Barry Welliver. Twenty-two Arizonans participated in the training session. Training concentrated on how to: "(1) assess and analyze seismic risks typical to school buildings; (2) develop actionable plans for reducing and managing these risks; (3) secure nonstructural components in school facilities; and (4) implement incremental seismic rehabilitation as an affordable approach for protecting existing school buildings and ensuring occupant safety."

FYI: The interactive Natural Hazards in Arizona viewer includes Quaternary fault themes and earthquake epicenter themes. The latter is updated frequently by AZGS' Jeri Y. Ben-Horin (earthquake geologist and manager of the Arizona Broadband Seismic Network).

AZGS Social Media Outlets: Status Report

The Arizona Geology Blog has been the primary medium for profiling topical geologic stories of interest to our stakeholders since 2007. We showcase AZGS and USGS geologic maps and reports, and we also post materials from other sources regarding new developments in Arizona geology (e.g., we recently summarized the Fraser Institute's 2020 survey of mining/exploration CEOs that showed Arizona surging to the top of mining jurisdictions worldwide).

Titles and links of several recent posts:

- June 04, 2021 - A Century of Fossil Discovery and Research at Grand Canyon
- April 22, 2021 - Arizona surges to the top of mining jurisdictions worldwide!
- March 24, 2021 - Arizona's Christmas Mine 1880s to 1982
- February 22, 2021 - AZGS Special Paper 12: Landslides along the I-17 corridor from Anthem to Flagstaff
- January 08, 2021 – Directory of Arizona's Active Mines – 2020

At the AZGS Facebook (~22,300 followers) and Twitter (~9,600 followers) nodes, we post daily on fresh developments in the geosciences and geologic investigations here in Arizona. Facebook posts reach an audience of between 2,000 and 5,000 daily, occasionally swelling to 20,000+ readers.

The AZGS Youtube channel hosts more than 100 videos, including more than 60 Arizona Mining Review episodes. Earthquake videos perform particularly well. Dr. Dave Brumbaugh's expose on Flagstaff-area Lake Mary Fault has been viewed more than 13,000 times since uploaded in 2012; viewing time of the 5-minute video totals 616.7 hours. More than 1,500 people subscribe to the AZGS Youtube channel.

The AZGS website is updated frequently to stay apace of developments in geologic hazards, publications, mining and mineral resources and other geology-related news.

AZGS Online Repositories & Databases:

- Document Repository: 121 years of geologic maps and reports published by the AZGS and its predecessor agencies that are freely available to view and/or download.
- Arizona Mining Data: ~16,000 unpublished reports, maps, drillhole data, and assays from 1000s of Arizona mines.
- Geologic Map of Arizona: interactive with broad unit descriptions.
- Arizona Geology Bibliography: comprising more than 13,000 citations published between 1890 and 2001.
- Geologic StoryMaps: includes themes on geotourism, the Holocene San Pedro River, walking geotour of downtown Phoenix.

All AZGS work is freely available to all to view and/or download.

Recent Theses and Dissertations in Geology from Arizona's Research Universities

Fieldnotes, predecessor to today's Arizona Geology, provided an annual compilation of theses and dissertations produced by graduate students in the geosciences at Arizona State University, Northern Arizona University, and the University of Arizona. We are reprising that feature in this summer issue.

A word of caution: In the case of Arizona State University and the University of Arizona, the university library provided the compilation. In both cases, the library receives formal submittals from their respective Graduate College. There may be a considerable lag between submittal and uploading the document and publishing the citation. Furthermore, M.S. theses are not required to be submitted to the University of Arizona library and may be unreported. Thus, the theses and dissertations reported here reflect a minimum. J. A. Wolkowinsky of Northern Arizona University's School of Earth and Sustainability graciously provided the NAU data included in this list. Citations were generated from all available information, but for embargoed theses and dissertations, page numbers were not always available. Theses and dissertations awared by out-of-state univeries are not listed. Each thesis may be sought for from the relevant university library, if not currently under embargo.

Arizona State University

Bercovici, H. L., 2020, The effect of bulk composition on the sulfur content of cores: Unpublished M.S. thesis, Arizona State University, Tempe, 42 p.

Brown, H. M., 2021, Geology of the Hassayampa River Canyon Area, Wickenburg, Arizona: Unpublished M.S. thesis, Arizona State University, Tempe, 46 p.

Dunham, E. T., 2020, To be or not to B: Meteoric implications for the galactic environment of Solar System formation: Unpublished Ph.D. dissertation, Tempe, 215 p.

Dunhlap, D. R., 2020, Chronology of planetesimal differentiation based on the timing of achondrite formation in the early solar system: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 161 p.

Ely, T., 2020, Thermodynamic cartography in basalt-hosted hydrothermal systems: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 478 p.

Gagler, D., 2020, Universal biochemistry within and across biological domains and levels of organization on Earth: Unpublished M.S.

thesis, Arizona State University, Tempe, 79 p.

Guild, M. R., 2020, Interactions between fluids, melts, and rocks in subduction zones: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 224 p.

Johnson, A., 2020, Investigations into crustal composition and oxidative weathering in the Archean: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 160 p.

Kim, J., 2020, Transitions in eruption style at La Fossa Cone, Vulcano Island, Italy: Unpublished M.S. thesis, Arizona State University, Tempe, 241 p.

Leong, J. A., 2020, Modelling geochemical and geobiological consequences of low-temperature continental serpentinization: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 355 p.

Loescher, G., 2020, Metal organic interactions at hydrothermal conditions: Useful transformations through geomimicry: Unpublished M.S. thesis, Arizona State University, Tempe, 94 p.

Ostrander, C. M., 2020, Refining Earth's ocean oxygenation history using molybdenum and thallium isotopes: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 275 p.

Peters, S., 2020, Investigating lava flow emplacement: Implications for volcanic hazards and planetary evolution: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 237 p.

Scott, T., 2020, Rock traits from machine learning: Application to rocky fault scarps: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 69 p.

Singh, V., 2021, On thin ice: Experimental spectroscopy and ice mechanics in support of ocean world exploration: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 247 p.

Torrano, A., 2020, Early solar system processes and parent body relationships recorded by chromium and titanium isotopes in meteorites: Unpublished Ph.D. dissertation, Arizona State University, Tempe, 186 p.

Northern Arizona University

Burch, S., 2021, Assessing fire impacts to a spring-fed riparian ecosystem during a dry climate cycle in Grand Canyon National Park, USA: Unpublished M.S. thesis, Northern Arizona University.

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